Rare-earth plasma extreme ultraviolet sources at 6.5-6.7 nm for next generation semiconductor lithography

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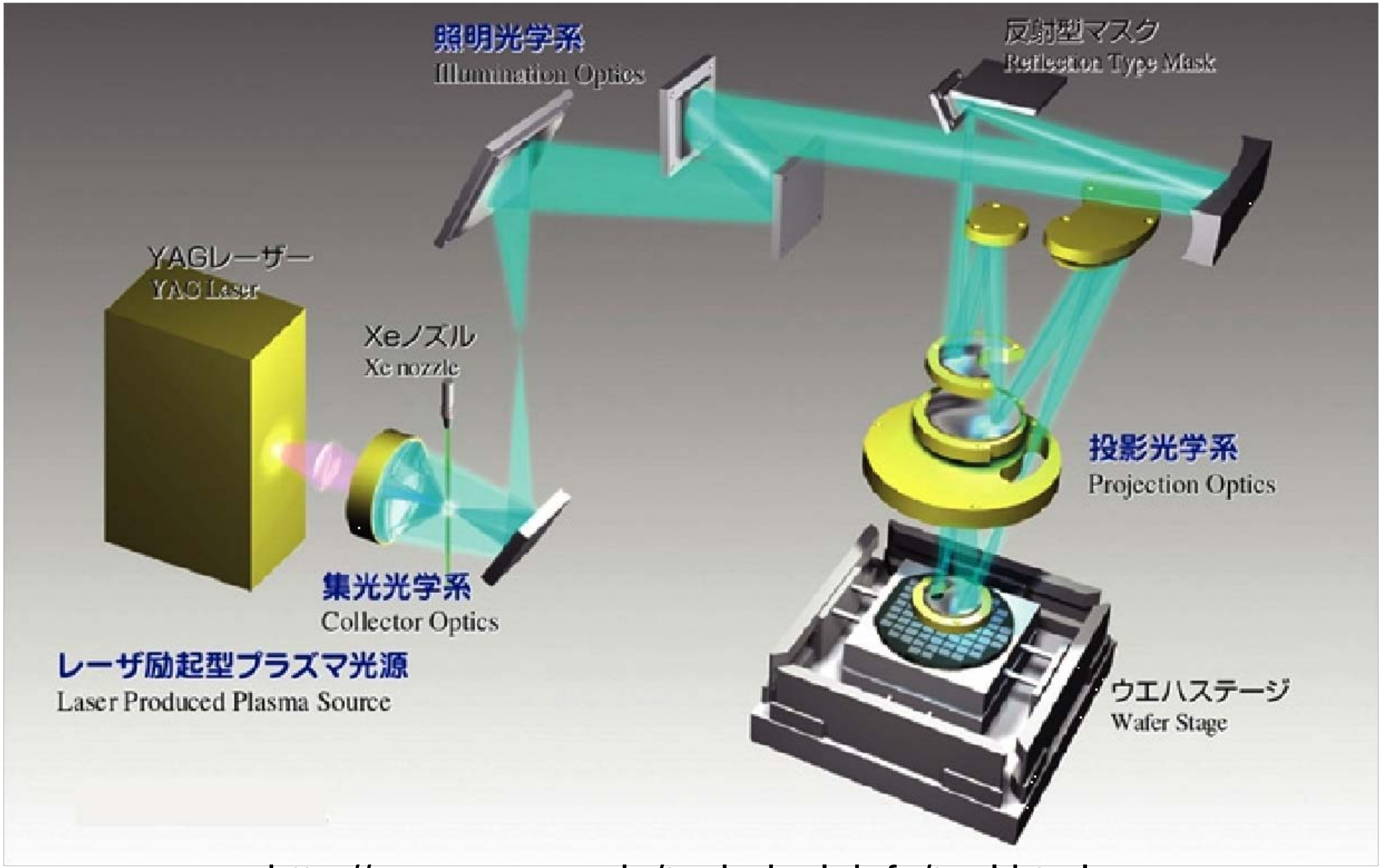
2010 International Workshop on EUV Sources
University College Dublin, Belfield, Dublin 4, Ireland
Sunday 14 November, 2010, 4:30 PM – 6:00 PM

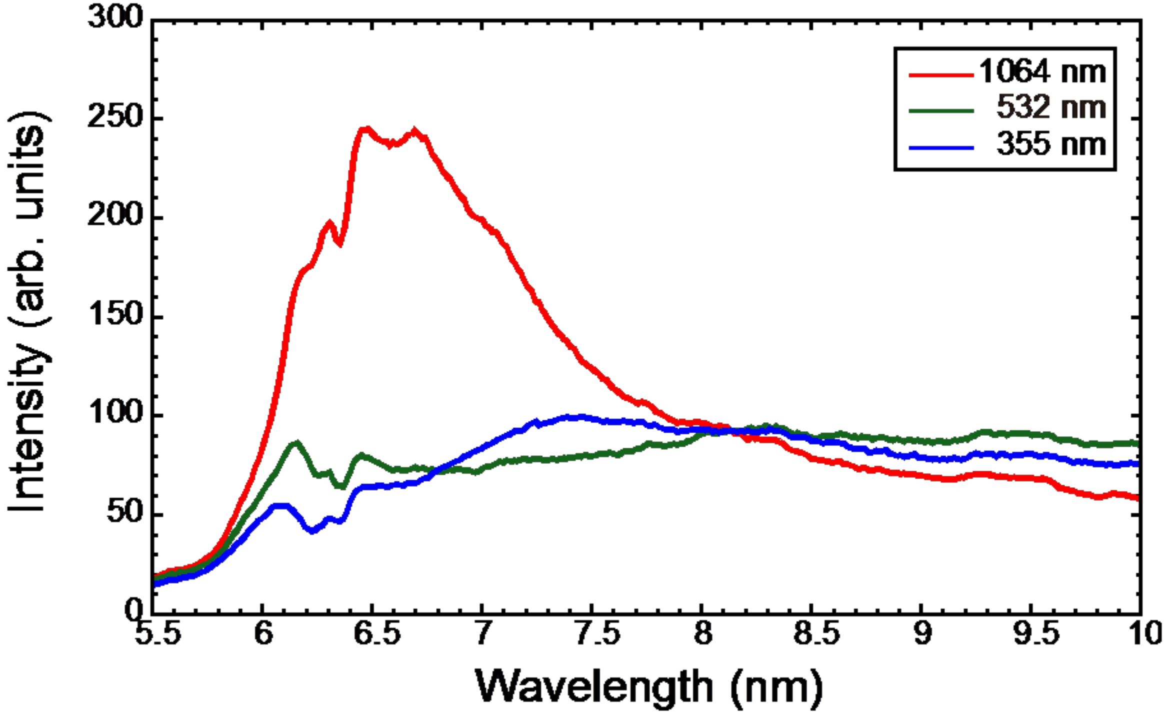
EUV lithography

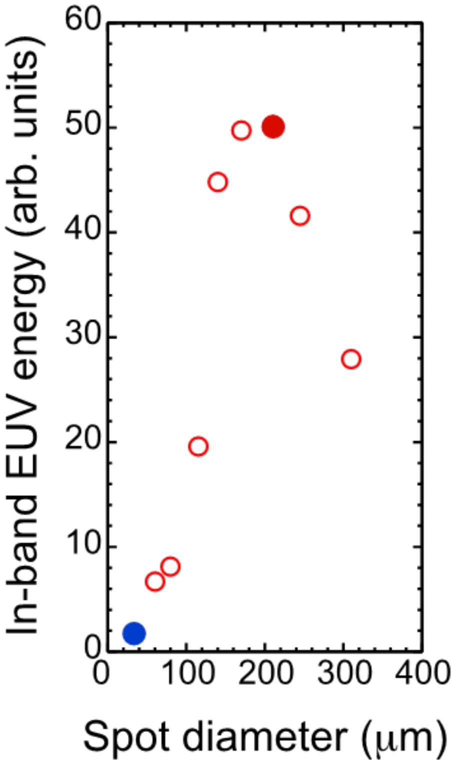


http://www.euva.or.jp/technical_info/tool.html

What's new
for high power and high CE

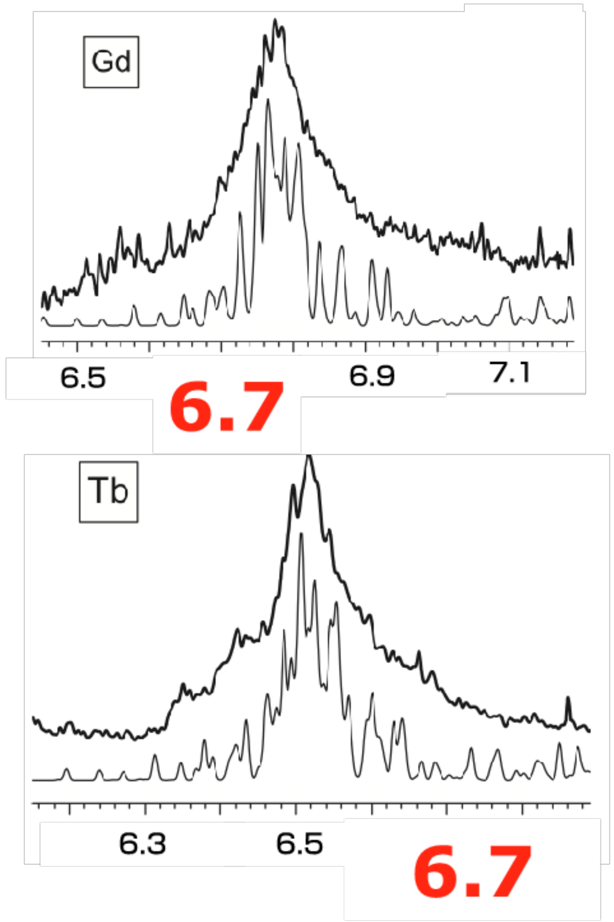
- Laser color dependence
- Initial target density dependences
- Enhancement condition of the 6.7-nm emission



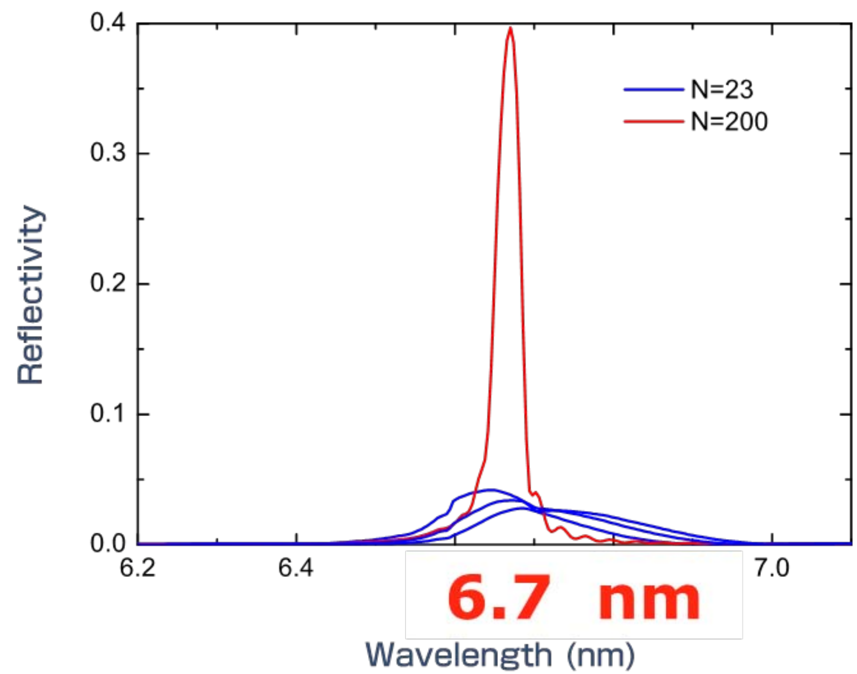


Introduction…
from previous presentation

6.7 nm: Gd, Tb plasmas

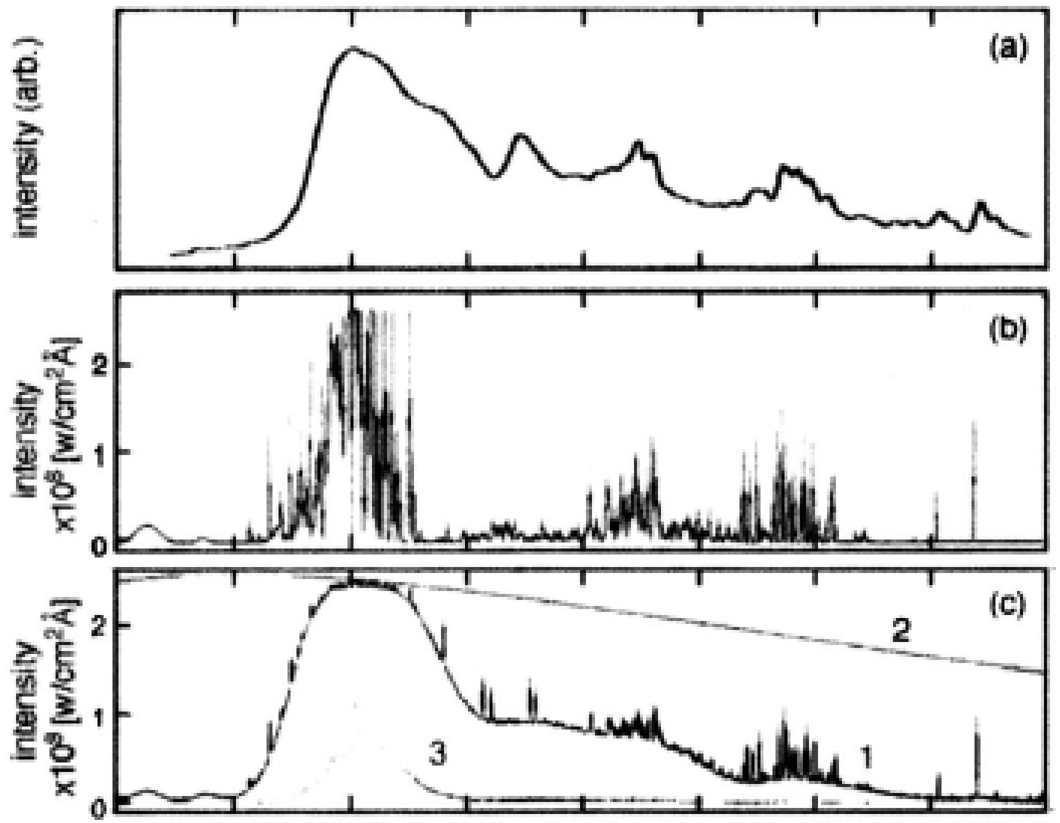


Mo/B_4C mirror



S. S. Churilov *et al*.,Phys. Scr. **80**, 045303 (2009).

However…we have a question!!!
May we observe spectral structure like Sn & Xe if we use the high-Z targets such as Gd & Tb?



Experiment@EUVA, Japan

Calculation w/o sutellite lines

Calculation ***w/ sutellite lines***

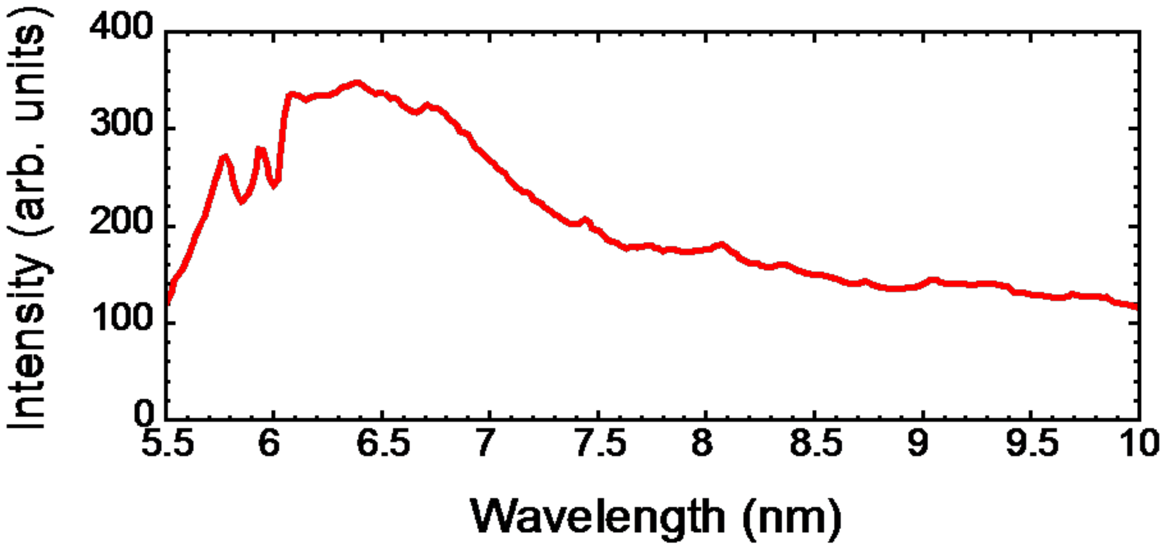
A. Sasaki *et al*., APL **85**, 5857 (2004).

Previous & recent observations

We observed continuum due to satellite lines

for absorption spectroscopy

for high power source by us

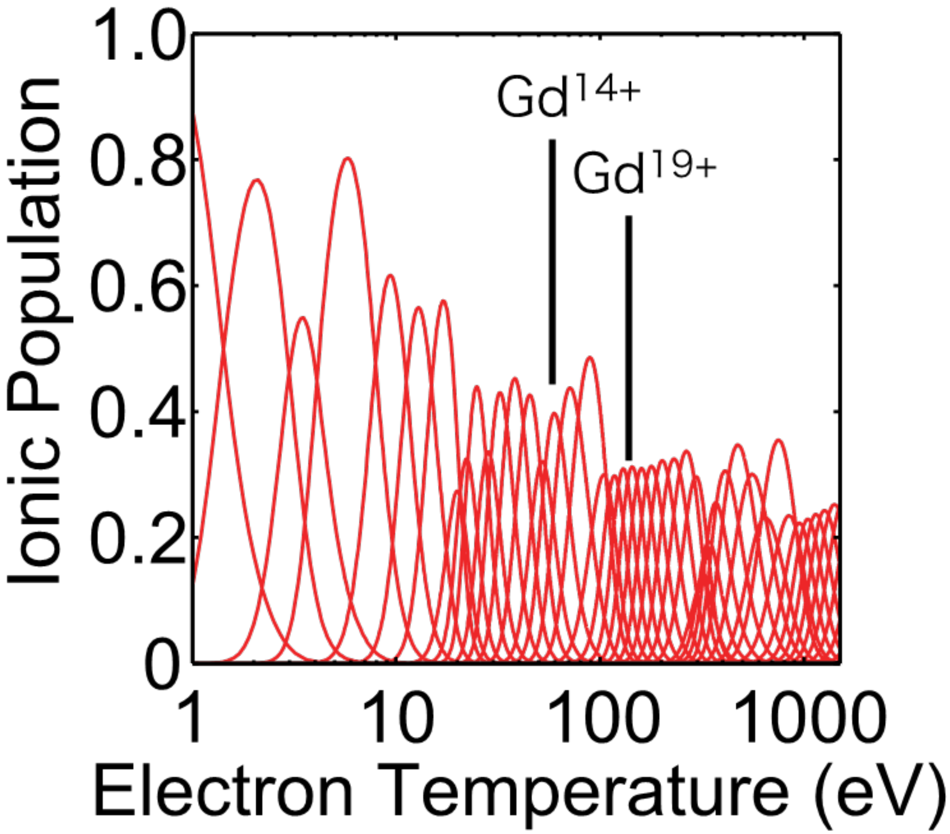


G. O'Sullivan & P. K. Carroll, JOSA **71**, 227 (1981).
T. Otsuka *et al*., APL **97**, 111503 (2010).

Objective

We demonstrate the efficient EUV source at 6.7 nm using Gd and Tb LPPs.

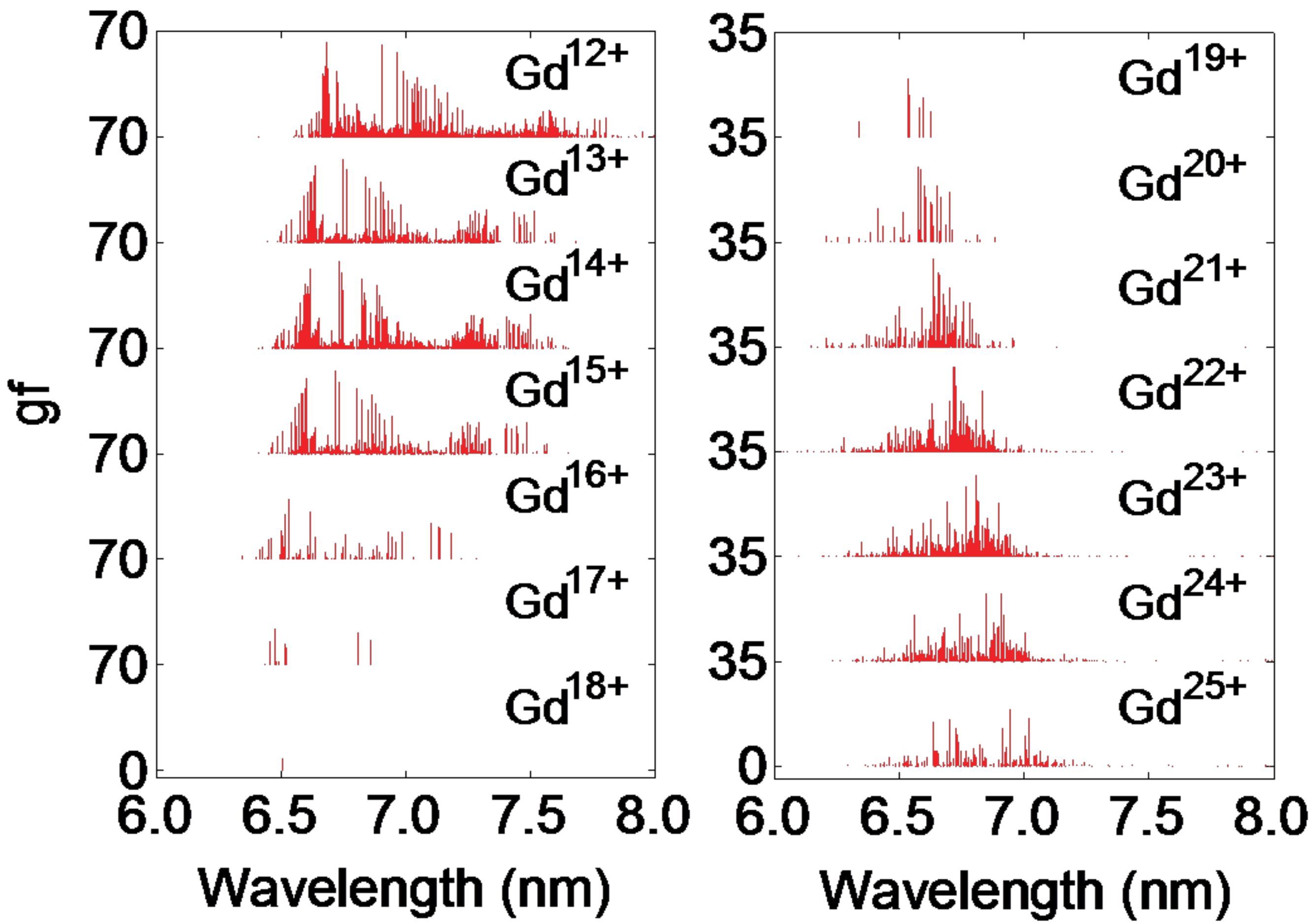
Ionic population of Gd ions
We should produce 50-150 eV plasma.



T. Otsuka *et al*., APL **97**, 111503 (2010).

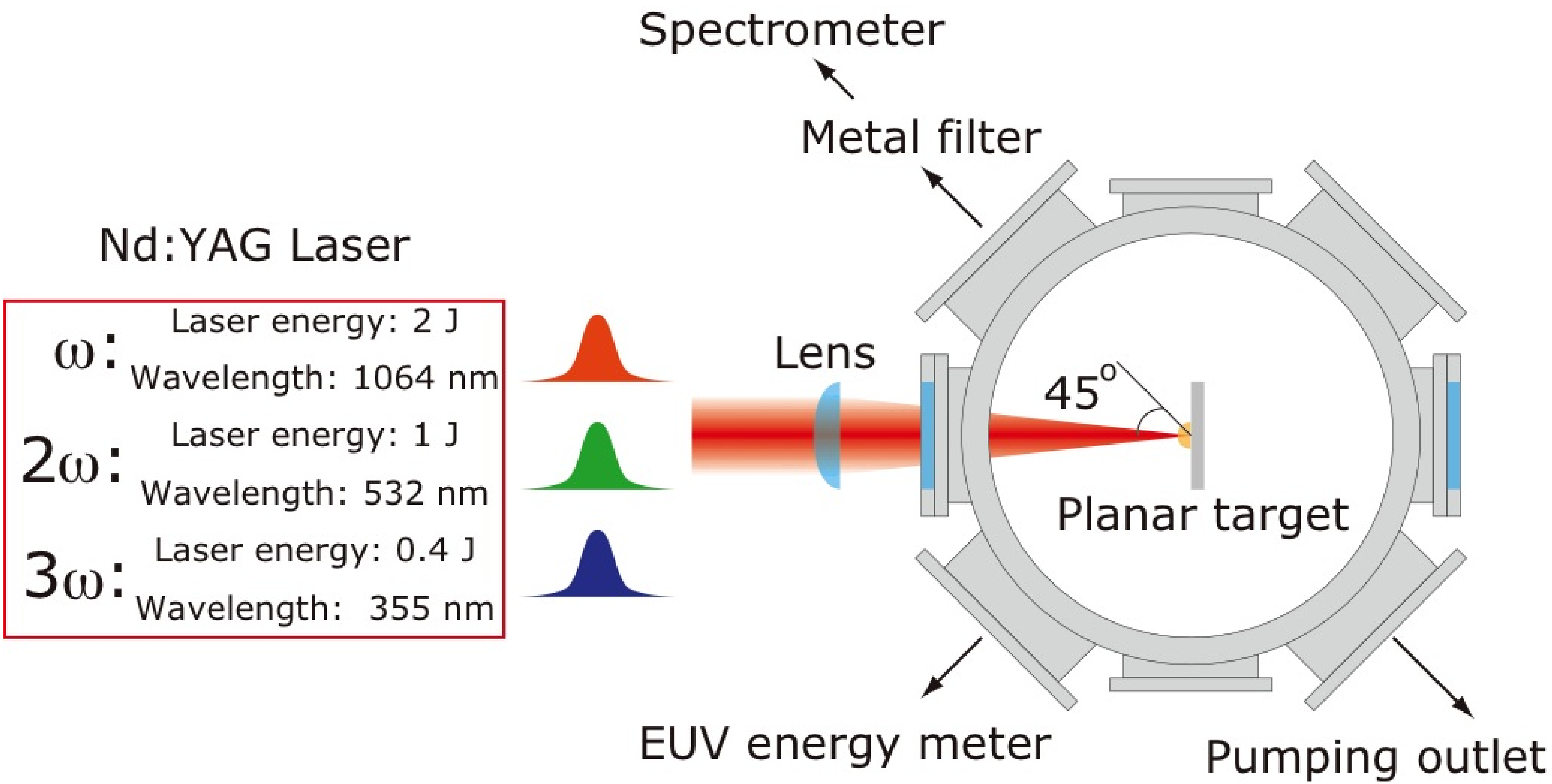
gf spectra of Gd ions

We confirm the UTA resonant lines around 6.7 nm

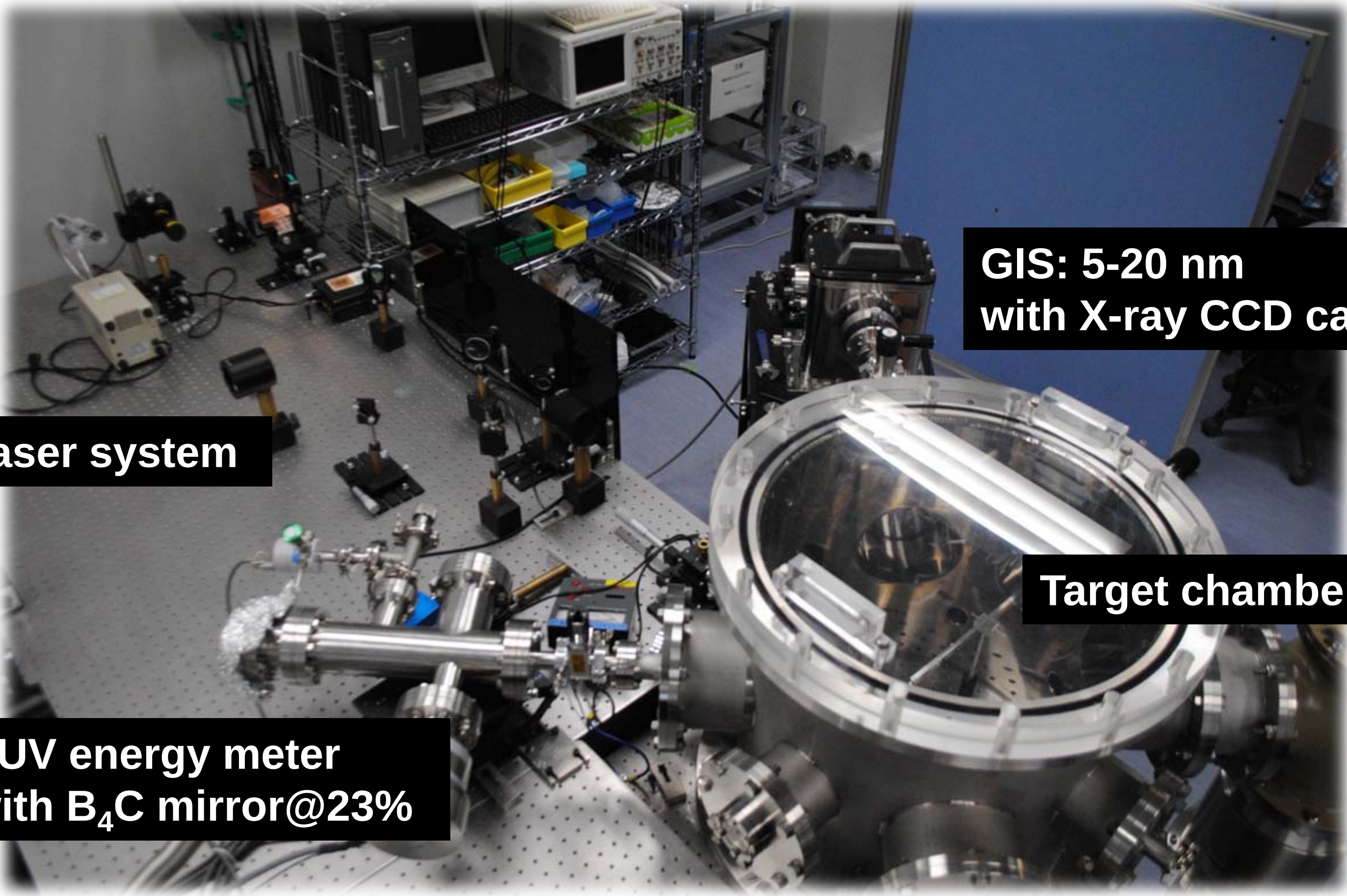


T. Otsuka *et al*., APL **97**, 111503 (2010).

Experimental setup

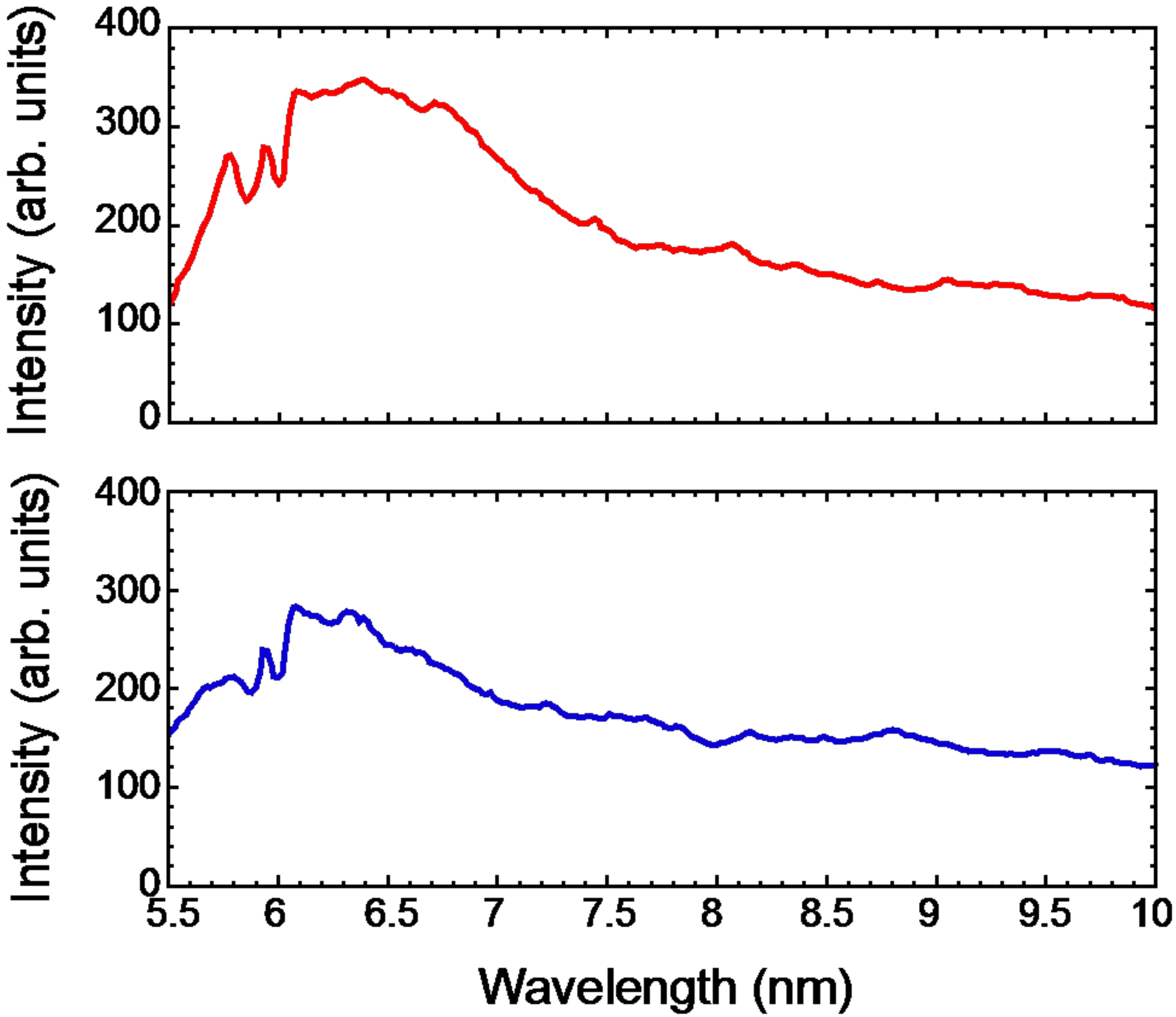


Photograph of our setup



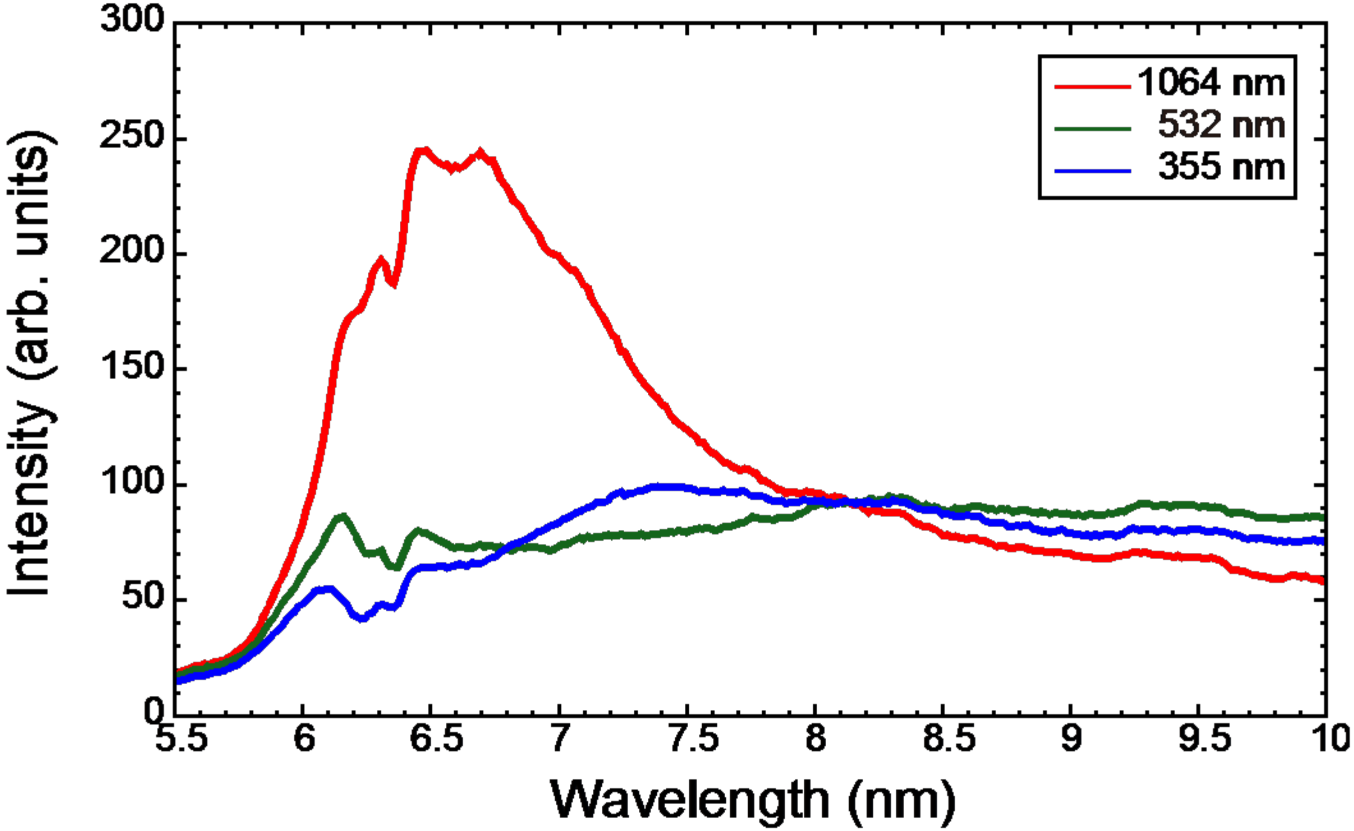
Spectral comparison Gd with Tb

We observed strong emission around 6.7 nm



Laser wavelength dependence

- Spot diameter: 50 um (FWHM)
- Laser energy: 320 mJ
- Laser intensity: 1.6 x 10^{12} W/cm^2



EUV CEs
(in 2% BW)

1064 nm: 1.1%

532 nm: 0.7%

355 nm: 0.5%

Laser wavelength dependence

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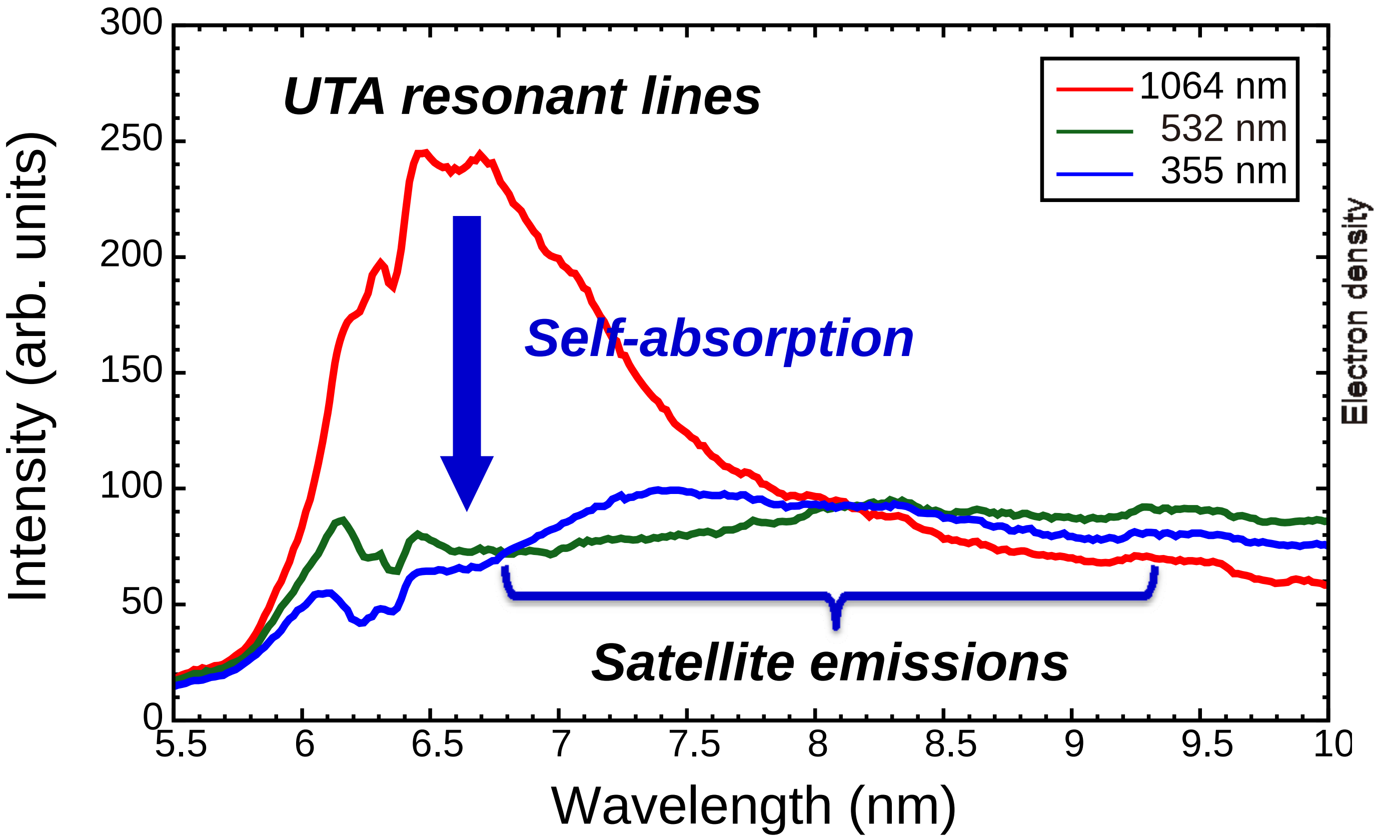
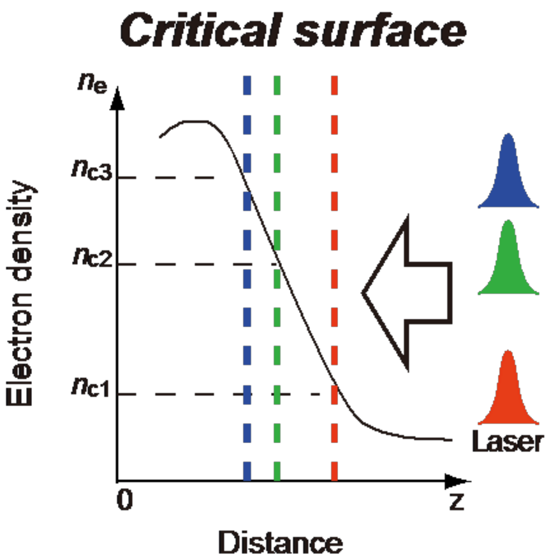
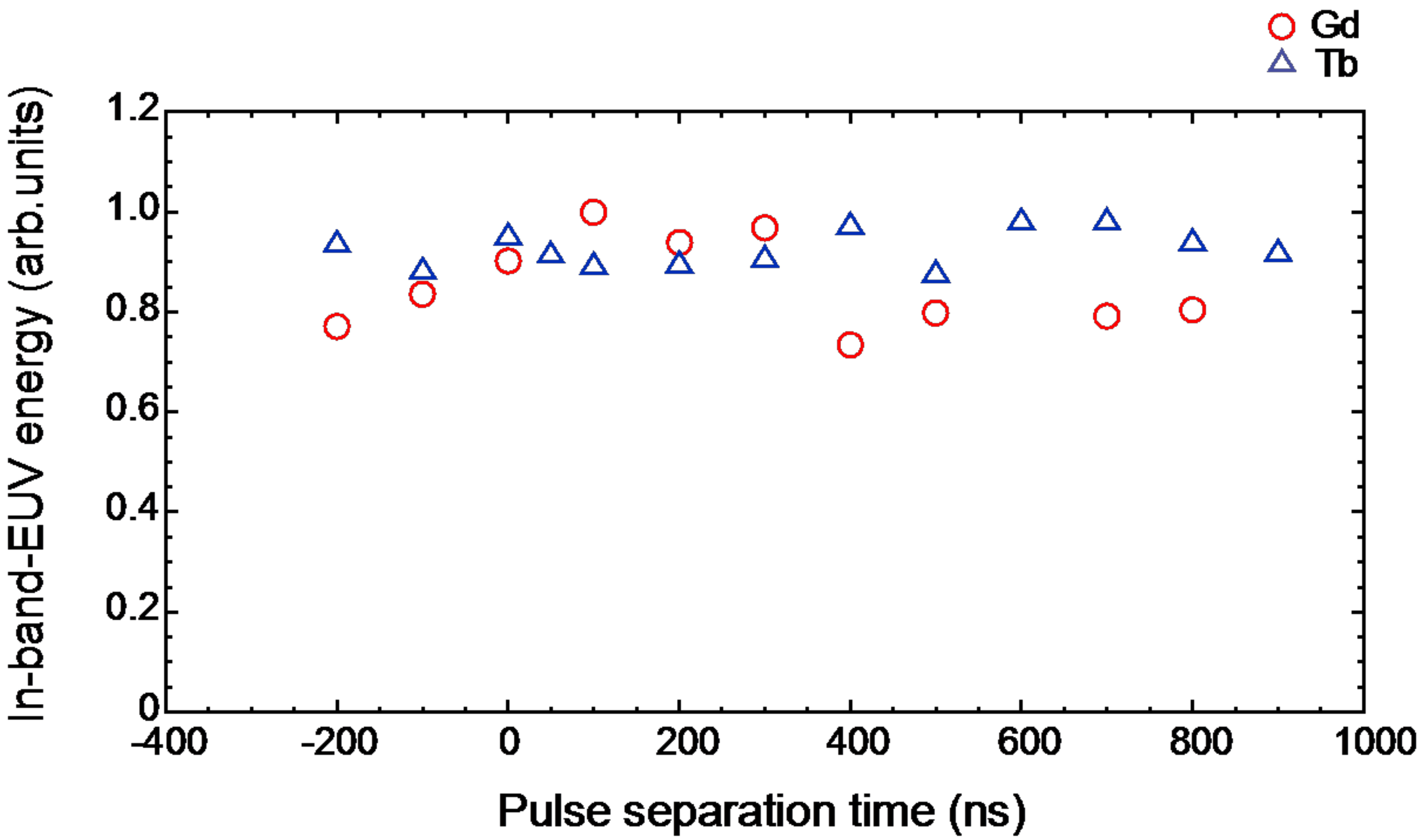




Dual laser pulse irradiation



Trade off 1
Effective ions vs self-absorption

Electron (ion) density decreases,
but ***absorption length increases***.

For large opacity material (high-*Z*), such as Xe & Sn

Electron density decreased: absorption effect decreased
Density gradient increased: absorption effect increased

For small opacity material (low-*Z*),
such as Li & low initial density target

Electron density decreased: absorption effect more decreased
Density gradient increased: large volume effect increased

Physical summary for high-Z plasmas
from 13.5-nm Sn plasmas

Low density plasmas for reducing self-absorption effects

Suppression of satellite emission & higher spectral purity

Long wavelength (low critical density): CO_2 laser@10^{19} /cc

Short laser pulse duration: ~1-2 ns@YAG laser (1064 nm)

Low density targets

Discharge plasmas (low density plasmas)

Effective dual pulse scheme

We require the use of:

low initial density target

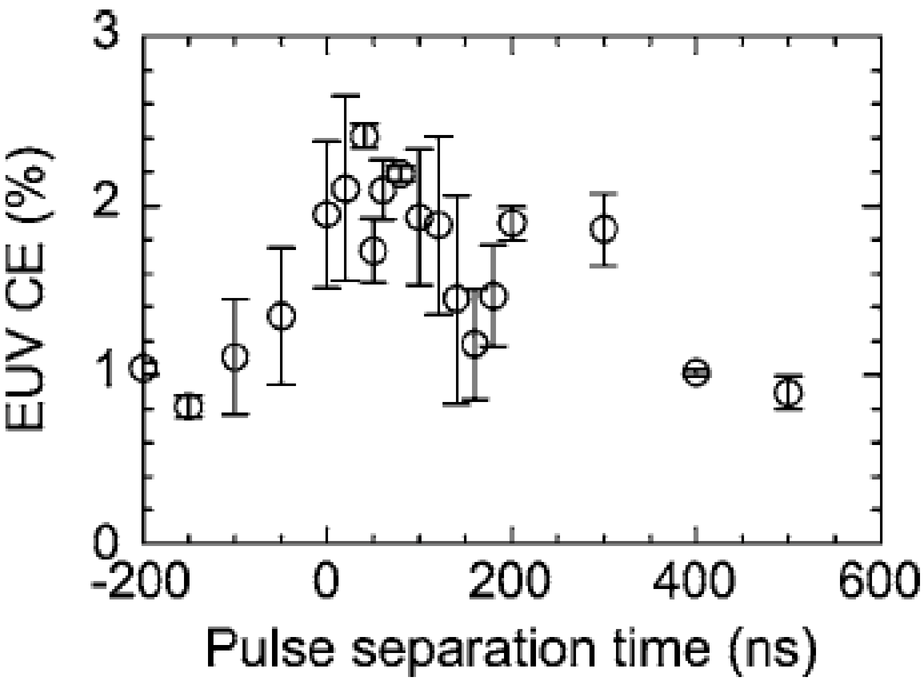
or

longer laser wavelength laser

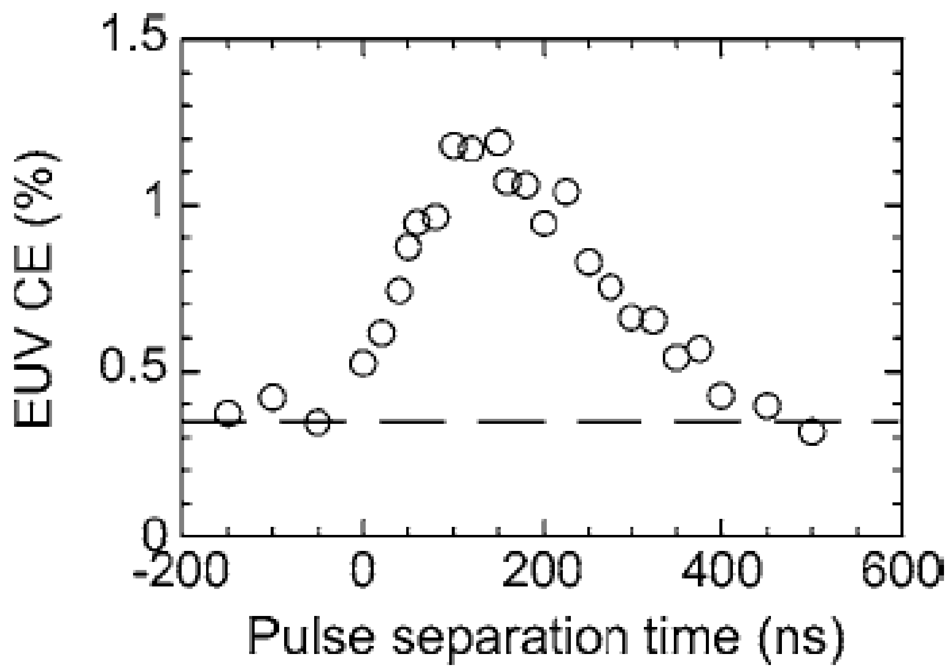
in the **self-absorption effect suppression** point of view.

Previous 13.5-nm dual laser pulse irradiation experiments

Low opacity: Li planar target

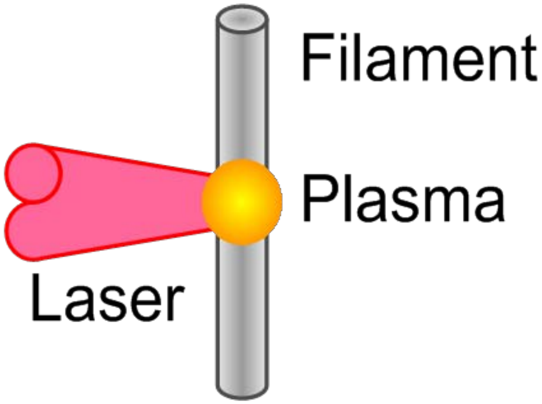


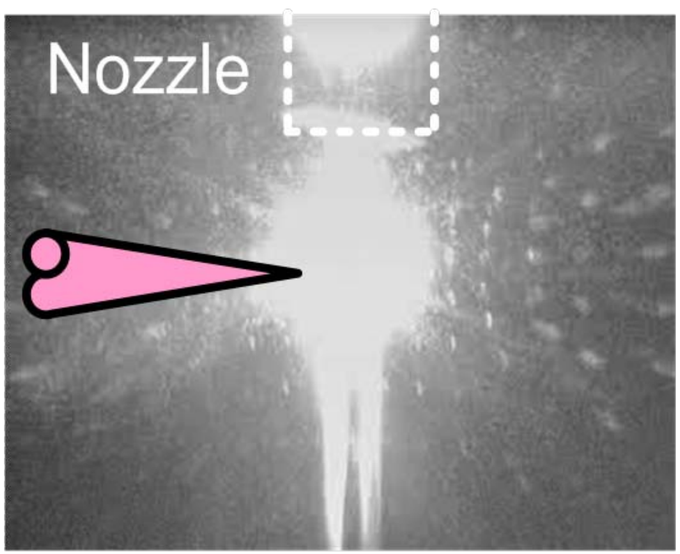
Low density: SnO_2 liquid target

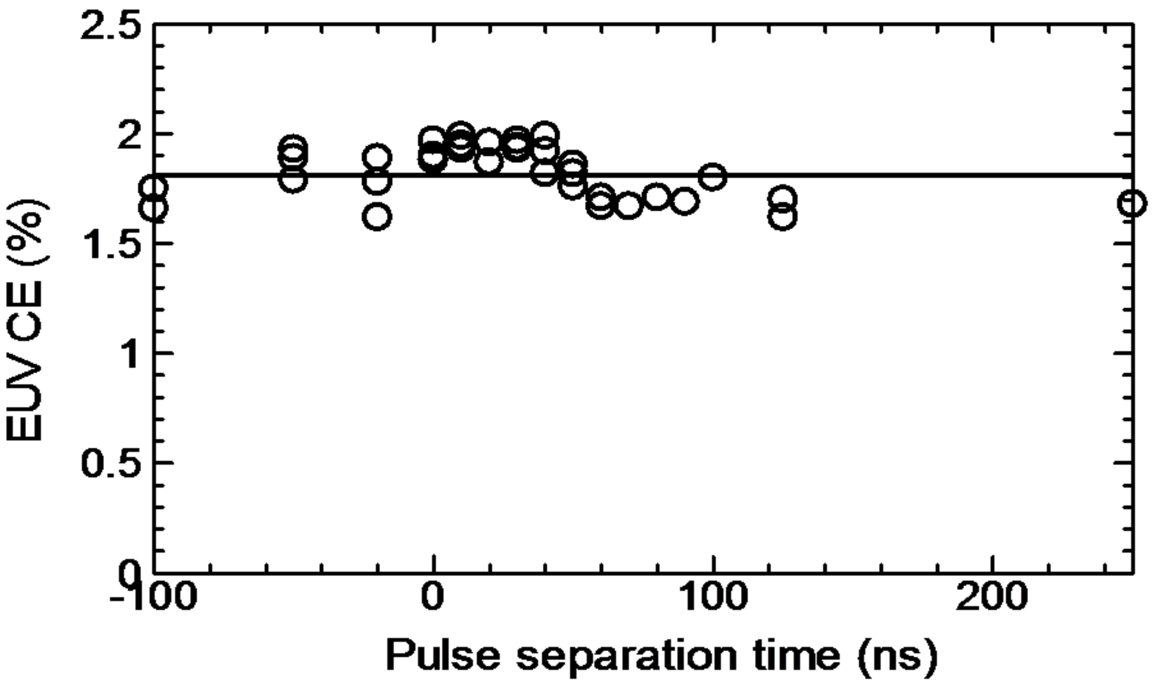


T. Higashiguchi *et al*., APL **88**, 161502 (2006).
T. Higashiguchi *et al*., APL **88**, 201503 (2006).

Previous 13.5-nm dual laser pulse irradiation experiments

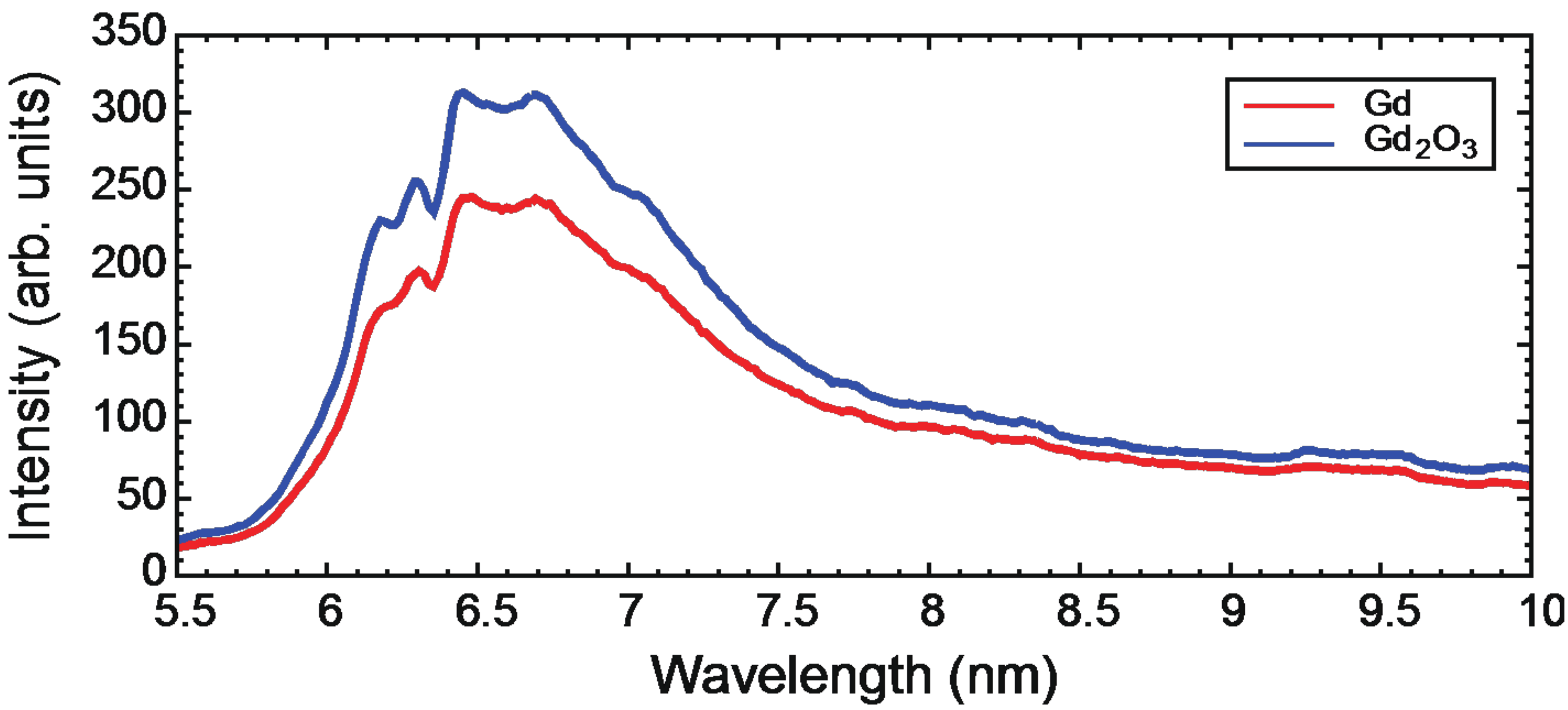




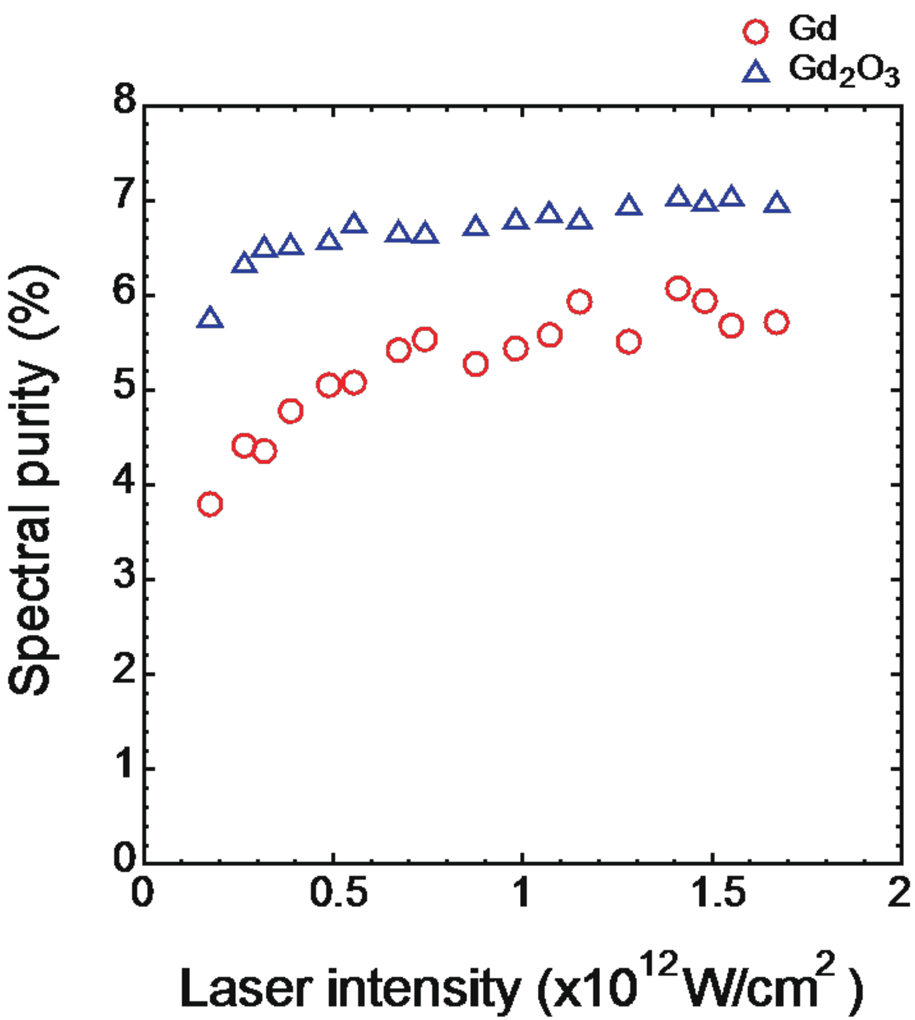


T. Higashiguchi *et al.*, RSI **78**, 036106 (2007).
T. Higashiguchi, (private communication, 2005).

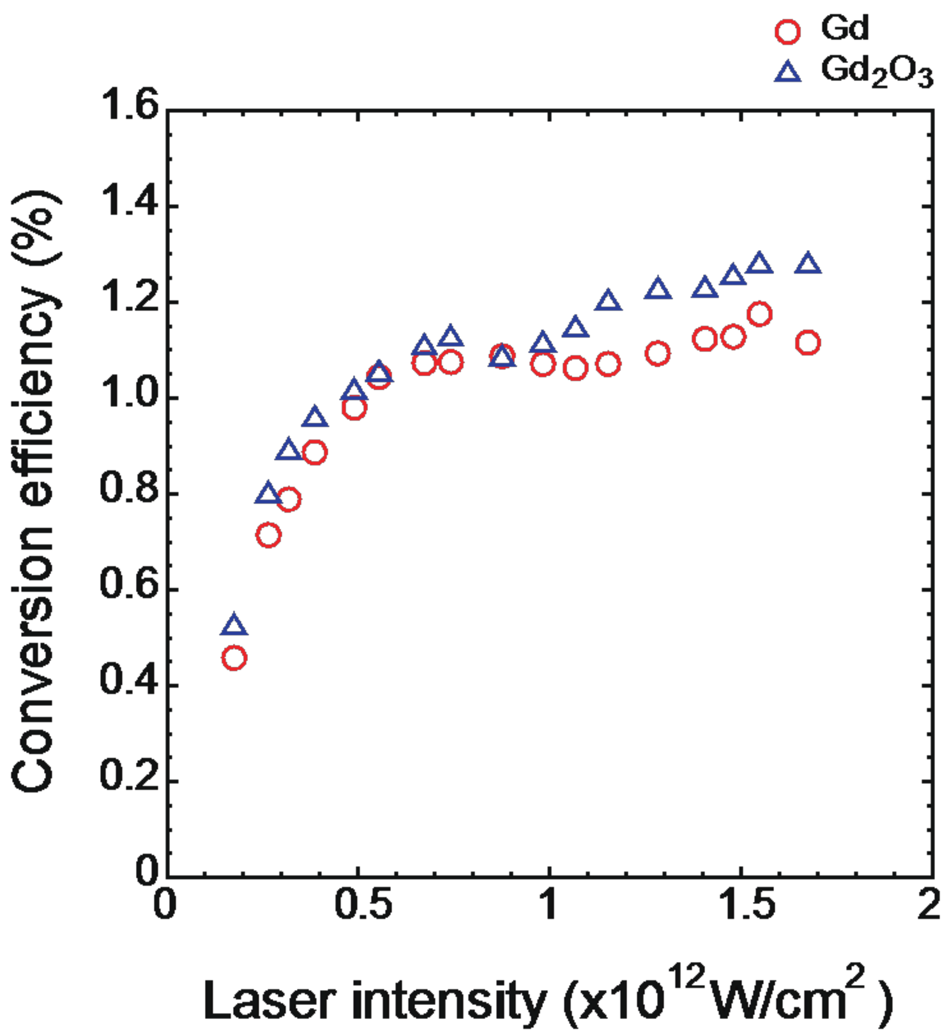
Target initial density dependence



Spectral purity



EUV CEs



Gd
Gd_2O_3
Conversion efficiency (%)
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
0
0.5
1
1.5
2
Laser intensity ($\times 10^{12}$ W/cm^2)

Trade off 2

High electron temp vs plasma expansion loss

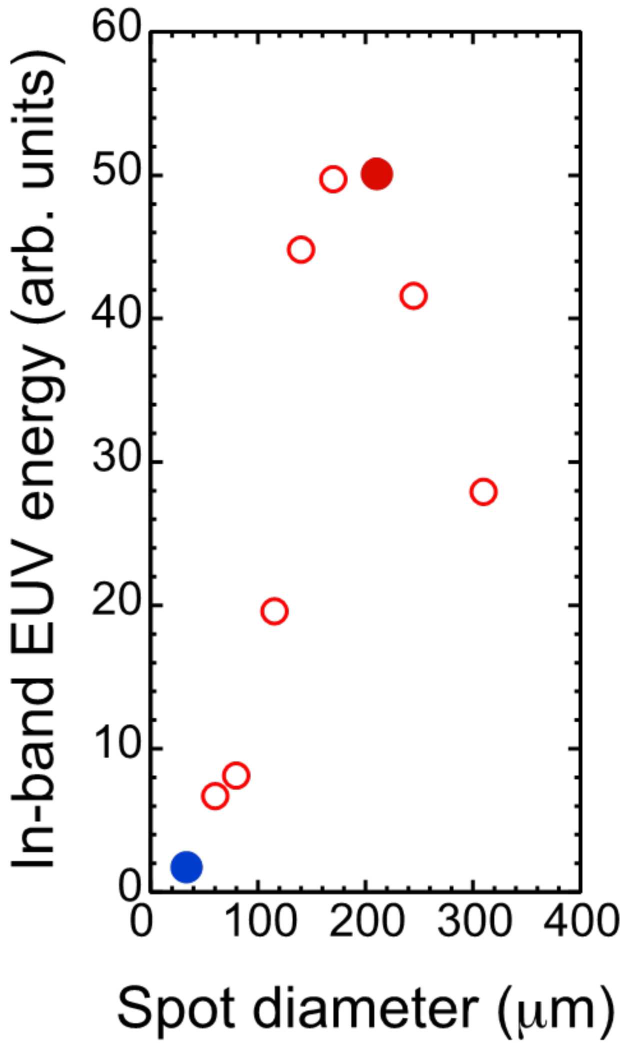
High T_e (50-150 eV) would be required

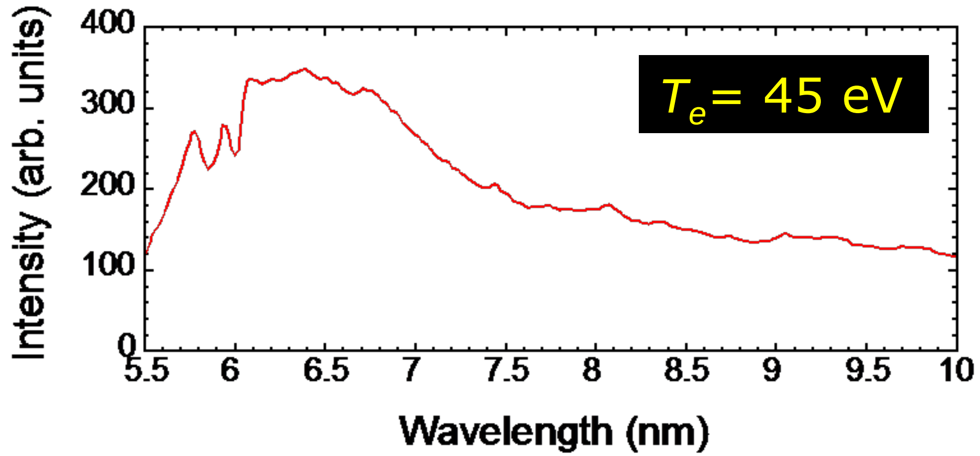
(small spot diameter)

Low expansion loss would be required

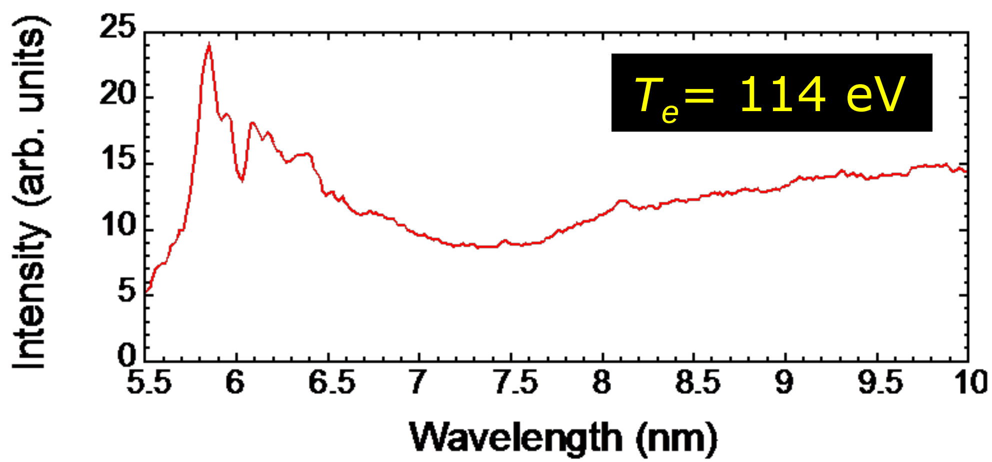
(large spot diameter)

Volume effect vs electron temperature





Spot diameter:210 μm Intensity: 4.0 x 10^{11} W/cm^2



Spot diameter:35 μm Intensity: 1.5 x 10^{13} W/cm^2

Question, problem, and definition…

- CO_2 laser-produced plasma behavior?

- High temperature (30-50 eV to 50-150 eV):
  high energy particles

- CE bandwidth (2% to less than 0.1%?)

Summary

We have demonstrated the efficient EUV source around 6.7 nm using Gd & Tb (rare-earth).

- Spectral behavior at different laser wavelength
- Low density target to ***suppress the self-absorption*** in plasma
- Conversion efficiency: **~ 1.3%** before optimizing parameters

- Dominated ***plasma hydrodynamic expansion loss reduction***
- Question, problem, and definition

Related paper & poster

APPLIED PHYSICS LETTERS **97**, 111503 (2010)

Rare-earth plasma extreme ultraviolet sources at 6.5–6.7 nm

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We have demonstrated a laser-produced plasma extreme ultraviolet source operating in the 6.5–6.7 nm region based on rare-earth targets of Gd and Tb coupled with a Mo/B_4C multilayer mirror. Multiply charged ions produce strong resonance emission lines, which combine to yield an intense unresolved transition array. The spectra of these resonant lines around 6.7 nm (in-band: 6.7 nm $\pm 1\%$) suggest that the in-band emission increases with increased plasma volume by suppressing the plasma hydrodynamic expansion loss at an electron temperature of about 50 eV, resulting in maximized emission. © *2010 American Institute of Physics*. [doi:10.1063/1.3490704]

T. Otsuka *et al*., APL **97**, 111503 (2010).
T. Otsuka *et al*., (submitted).

Related paper & poster

Rare-earth plasmas as next generation extreme ultraviolet lithography sources at 6.5-6.7 nm

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